THE ELECTRON CLOUD INSTABILITY STUDIES IN BEPC*

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Abstract

The electron cloud instability (ECI) in the BEPC was studied systematically with experiments and simulations in recent years. Several electron cloud detectors have been installed into the BEPC storage ring to measure the electron yielding. The effects of solenoid, the clearing electrode, the chromaticity and the octupole on ECI have been investigated in BEPC experimentally. To evaluate the ECI in BEPCII, the upgrade project of BEPC, a computer code has been developed to simulate the electron density in the antechamber under different conditions, as well as the progress of the single bunch and coupled bunch instabilities caused by the electron cloudy. The experimental and simulation results, as well as the activities are reported in this paper.

INTRODUCTION

Since the ECI was first observed on the BEPC in 1996 [1], many experiments have been carried out to study the characteristics of the ECI, the generation of electron cloud (EC), and its effect on the beam performance. Meantime, analyses and simulations on the ECI in the BEPC storage ring were also done [2]. Now BEPC is being upgraded to a two-ring collider, namely BEPCII, with electron and positron beams circulating in each separate ring. Thus ECI may possibly influence the beam performance in the positron ring as observed in KEKB and PEPII. As one effective way to reduce the EC, antechamber with TiN coated beam pipe will be adopted in BEPCII. Then a computer code has been developed to estimate the EC density in the beam pipe versus different width of the antechamber and the secondary electron yield. The single and coupled bunch instabilities due to EC are also simulated. Meantime, to get more practical experience for BEPCII, experiments were continued on BEPC in recent years, such as ECI measurement, using solenoid, clearing electrodes of both a special detector and BPM buttons, as well as octupole to cure ECI.

In this paper, the main experiment results are reviewed with focus on EC measurement and restraining method such as solenoids, clearing electrodes, chromaticity and octupole. Then the simulation studies about the ECI in BEPCII are introduced sequentially on the EC density, the single and coupled bunch instabilities. A summary with some discussion on the results is given at last.

EXPERIMENTAL STUDIES

The main parameters of the BEPC for the typical experimental studies are listed in Table 1.

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Table 1: Parameters for BEPC experiments.

Parameter (unit)	BEPC
Beam energy E (GeV)	1.3
Betatron tune ν_x/ν_y	5.82/6.74
Bunch spacing L_{sep}(m)	1.5
Natural emittance ε_x (nm-rad)	134
RF frequency f_{rf} (MHz)	200
Harmonic number h	160
Transverse damping time $\tau_{x,y}$ (ms)	86

The instrumentations used in the experiments include tune measurement system, BPM system, synchrotron light monitor, spectrum analyzer, and streak camera etc.

First stage studies on ECI phenomena

The first experiment on the ECI was performed in 1996. A typical chart of the vertical betatron sidebands which were observed on the spectrum analyzer is as shown in Fig. 1, when the positron beam was injected to 9.3 mA with 160 uniformly distributed bunches, while the similar phenomena were not found in the case of electron beam under the same conditions. So this vertical coupled bunch oscillation can be attributed to the electron cloud accumulated in the ring with positron beam. We then started observation on the parameter dependence of ECI, such as bunch spacing, the beam energy, beam emittance, closed orbit, chromaticity, etc, as the first stage of experimental studies until 1998.

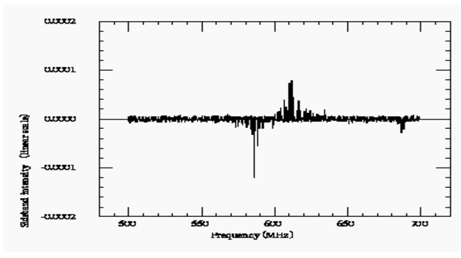

Figure 1: The vertical betatron sidebands.

In the experiments, the instability strongly depends on the bunch spacing, as the threshold current of the instability was higher than 40 mA when the positron bunches were filled by every two RF buckets. The experiment of beam emittance effect on the ECI showed that the smaller the emittance, the higher the threshold current.

The chromaticity can affect the threshold of the instability. At a beam current of 9.6 mA with 160 bunches, the vertical betatron sidebands disappeared when chromaticity was tuned from 4 to 6, and the sidebands reappeared when the chromaticity changed back to 4. The instability can be suppressed by a larger chromaticity. The energy dependence of the instability is done by scanning from 1.3 GeV to 2.2 GeV at a beam current of 10 mA with 160 uniformly filled bunches. The observed chromaticity dependence on energy at the threshold of the instability is as shown in Fig. 2, that the higher the beam energy, the lower the chromaticity required to damping the instability.

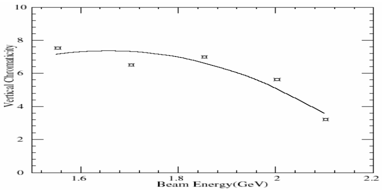

Figure 2: The chromaticity dependence on beam energy at the threshold of the instability

The octupole effect on the instability was also tested preliminarily in the first stage experiment. The sidebands of instability could be suppressed when the octupole was excited on.

A fast beam position monitor system supplied by KEK, was used to study the bunch oscillation process in May 1998. The damping time and the coupled bunch modes were obtained by fitting and doing FFT to the oscillation data recorded. This mode analysis gave a clear picture that the instability is different between positron beam and electron beam under the same conditions.

Electron cloud measurement

EC detectors were installed in the storage ring since 1999. The typical structure of the detector is shown in Fig. 3 with the similar structure like that used in APS [3]. With the first detector, we got some information on the PE energy distribution, dependences of beam parameters. From 2002, other 4 detectors were designed and installed on different positions of the storage ring [4,5].

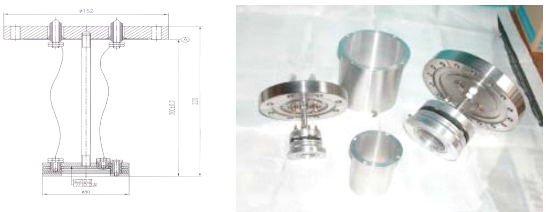

Figure 3: The detector structure for EC measurement

The detailed EC measurements were carried out using the detectors. The detector current I_c varies linearly with the total beam current I_b, and it did not saturate as the I_b was not yet strong enough. The EC energy distribution was deduced from the bias voltage scan. The dependences of I_c on beam energy, chromaticity, and emittance are not sensitive at the same closed orbit. The coupled bunch oscillation caused by ECI dose not influence the yield of EC measured.

The multipacting effect has been investigated by filling the positron beam with different bunch spacing, but there is no obvious enhancement of I_c/I_b by varying the bunch spacing when we used a detector near by the magnet. We suspected this due to the photon electron is dominant nearby the exit of magnet, so another detector was installed far away from the magnet, more experiments are needed to check the multipacting effect.

Solenoid effect on ECI

It was verified in KEKB [6] and PEPII [7] that solenoid field along the beam axis is very effective to suppress ECI. From the measured I_c by the first electron detector when solenoid was wound on the beam pipe nearby, it was clear that the solenoid really affect the EC density. Thus during the shutdown of BEPC last year, we wound solenoids in most straight sections around the BEPC storage ring to study its effect.

The total length of the solenoid wound on the straight sections is about 42 meters, covering about 18% of the ring circumference. Some pictures of solenoid winding are shown in Fig. 4. All the solenoid parts covered on different straight sections are connected in series. A DC power supply can provide a current up to 35 A to the solenoids which corresponds to about 30 Gauss magnet field along the beam path.

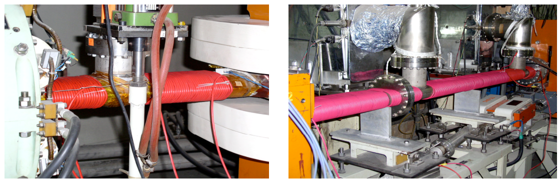

Figure 4: The solenoid wound on the vacuum chamber.

To study the solenoid effect on coupled bunch instability, a multi-bunch positron beam is filled to the threshold current of ECI, we observed clear sidebands of oscillation when chromaticities were set to $\xi_{x,y}$=1.5. When a current of 15 A is powered to the solenoid, both left and right sidebands disappeared, shown in Fig. 5.

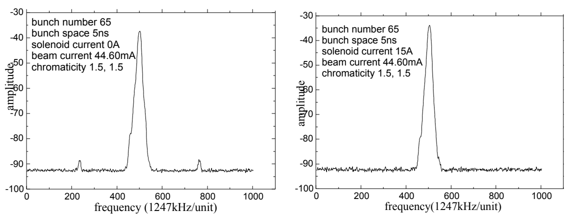

Figure 5: Solenoid effect on vertical betatron sidebands (left: solenoid off, right: solenoid on).

To study the solenoid effect on single bunch, a streak camera was used to observe the change of the vertical bunch size on/off solenoids. We take the 5th bunch from the tail of bunch train for estimation. If the solenoids on, the vertical bunch size is reduced about 15% in average as shown in Fig. 6.

Similar experiments were repeated under different connection scheme of the solenoid parts between the arc and straight section. From the experiments, it can be seen that the solenoid is more effective in the arc section nearby the magnet than in the long straight section far away from magnet, and the polarity of the solenoid is not important.

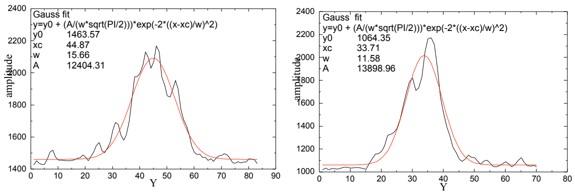

Figure 6: The vertical bunch size observed on streak camera as the solenoid off (left) and on (right).

Clearing electrode effect on ECI

Two kinds of clearing electrode have been tested in the experiment. First, a newly installed EC detector can be used as an electrode to clean the EC with a properly DC voltage given on an extra grid inside, while another detector which locates just above it on the top, can be used to measure the change of EC after applying the electrode, as shown in Fig. 7. One typical measured electron current I_c as a function of the applied voltage is also shown in Fig. 7.

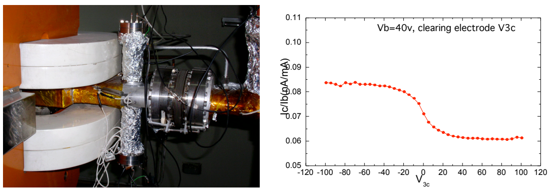

Figure 7: The picture of the detectors used as clearing electrode and the measured I_c vs. the voltage.

It is observed that the EC density decreases as the voltage applied on the electrode increases, and saturates gradually as the applied voltage is high enough. This result encourages us to do more experiment using the buttons of the BPM as clearing electrodes.

There are 32 BPMs for orbit measurement on the BEPC storage ring. With a special switcher, the total 128 circular BPM buttons can be supplied DC voltage in the same time. In each BPM, the 4 buttons are labelled as A, B, C and D, respectively, as shown in Fig. 8. All the 32 buttons of A or B or C or D can be as different groups to be applied DC voltages. DC voltages from −600V to +600V were supplied to the different patterns of buttons.

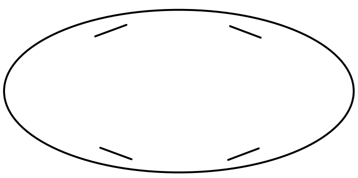

Figure 8: BPM button labelling (A,D: inboard side of the ring, B,C: outboard side).

At the beam conditions of the ECI, we scanned the applied voltage on the BPM buttons and measured amplitudes of the observed betatron sidebands. The best pattern is to apply +600V on all A and D buttons, and in the meantime, apply −600V on all B and C buttons. In this pattern, the amplitudes of sidebands are 20% less than the case without any DC voltages on the BPM buttons. In this way, the amplitudes of sidebands and the vertical beam size observed of head bunch and tail bunch vs. the voltages on the BPM buttons are shown in Fig.9.

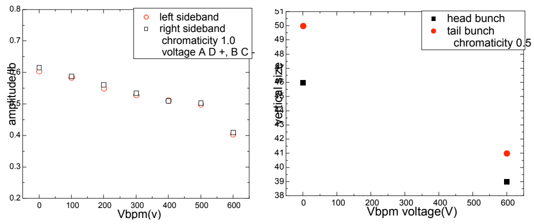

Figure 9: Electrode effect on sideband (left) and bunch size (right) vs. voltage on the BPM buttons.

Chromaticity effect on ECI

An effective way to suppress the ECI is to enhance the chromaticity, which had already been verified in BEPC. Higher chromaticity can not only lower the amplitude of sidebands, but also reduce the bunch size. On average, the bunch size is reduced about 30% when the chromaticity is enhanced from 1.5 to 4 in the case of solenoid field off. The amplitudes of sidebands and the vertical bunch size observed of head bunch and tail bunch vs. the chromaticity are shown in Fig. 10.

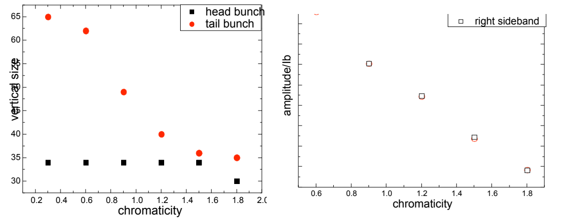

Figure 10: Amplitude of sideband (left) and bunch size (right) vs. chromaticity.

Octupole Effect on ECI

There was one octupole located in the dispersion free straight section of the ring. Its effect against ECI was tested at the threshold beam current of ECI. When the octupole is excited with a DC current of 1.0A, the vertical sidebands of ECI disappeared and the bunch size of the tail bunch is suppressed about 20%, shown as Fig. 11. It is expected that the octupole can increase the Landau damping, however, its effect to suppress the vertical bunch size needs further investigation.

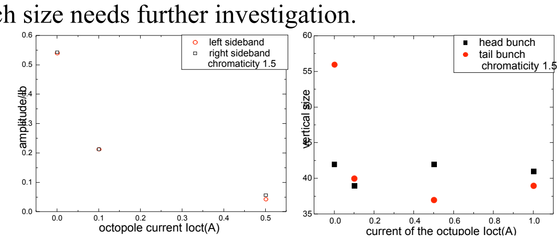

Figure 11: Amplitude of sideband (left) and bunch size (right) vs. octupole strength.

SIMULATION STUDIES FOR BEPCII

BEPC is currently being upgraded to a two-ring machine with a luminosity goal of 10^{33} cm^{-2}s^{-1}. The ECI is suspected to occur in the positron ring and influence the luminosity performance of the collider, so an antechamber with absorber will be used in the arc section of the ring, and TiN will be coated inside beam chamber. To evaluate the ECI practically, a code [8] has been developed to simulate the EC density distribution in antechambers. The coupled bunch instability and the beam blow up as the head-tail model are also studied with the code. The main parameters relating the ECI are listed in Table 2. The typical structure of antechamber in the arc and the equivalent cross section of beam pipe used in the simulation code are as shown in Fig. 12.

Table 2: Parameters of the BEPCII

Parameter (unit)	BEPCII
Beam energy E (GeV)	1.89
Bunch population N_b (10^{10})	4.84
Bunch spacing L_{sep} (m)	2.4
Rms bunch length σ_z (m)	0.015
Rms bunch sizes $\sigma_{x,y}$ (mm)	1.18,0.15
Chamber half dimensions $h_{x,y}$ (mm)	60,27
Slippage factor η (10^{-3})	22
Synchrotron tune Q_s	0.033
Betatron tune ν_x/ν_y	6.53/7.58
Circumference C (km)	0.24
Average beta function (m)	10

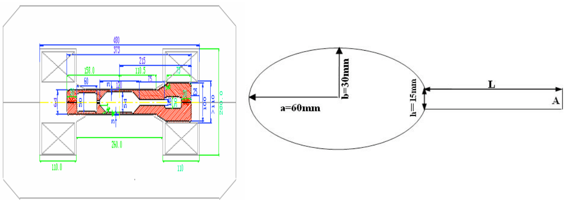

Figure 12: The antechamber structure (left) and the simplified model used in the code (right).

Electron Cloud

We only consider tow main sources of electrons [9], namely: (1) photoelectrons arising from the synchrotron radiation hitting the wall of the vacuum chamber, and (2) secondary emission from electrons hitting the walls. Because of antechamber, only ~0.5% photons remain inside the beam pipe. Photoelectrons are produced in the chamber and antechamber by the photons hitting on the wall with yield rate Y~0.1 and reflectivity R~0.1. If there is photon absorber, the Y and R become as small as Y~0.02, R~0.1. The percentage of photoelectron escaping out of the antechamber depends on the width of antechamber. In the simulation, the beam field is represented by the Bassetti-Erskine formula [10], and the numerical solver Poisson-Superfish in the central region of ($10\sigma_x$,$10\sigma_y$) and out of this region, respectively. In the simulation we assume that secondary electrons yield (SEY) with and without TiN coating in the chamber is 1.06 and 1.8, respectively.

The line density of EC along the chamber and the volume density of EC in the central region (10σ of transverse beam size) of the chamber can be obtained from the simulation. Since the central part of electron cloud is much effective to act on the beam, it is usually counted as EC density in the simulation. The EC distribution in the different shape of the vacuum chamber, and the comparison to that with two electrodes placed near the entrance of the antechamber are shown in Fig. 13. It can be seen that the antechamber and the electrode help to reduce the electron density, especially in the central region of the chamber where the beam passes through. The electron density decreases as the voltage on the electrode increases, and the effect will be saturated around 600V at the BEPCII parameters.

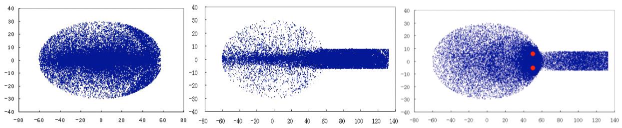

Figure 13: The electron distribution in the elliptical chamber (left), in the antechamber (middle) and in the antechamber with electrode (right).

The EC density accumulated along the bunch train in antechamber with different width is shown in Fig. 14. The EC density is reduced 5 times if the antechamber width L is about 5 times to the chamber height h. Fig. 14 also shows that the electron density will saturate when about 20 to 30 bunches pass, and will dissipate quickly through about 10 empty RF buckets.

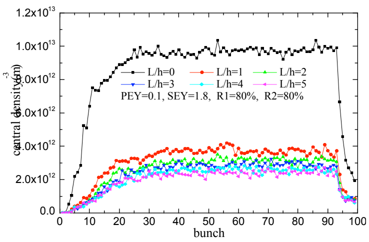

Figure 14: EC density versus width of antechamber.

Simulations with different values of the SEY shows that the EC density increases quickly when δ_{max}>1.6, thus TiN coating is necessary for reducing EC density.

Simulation results show that the EC density can be reduced by about 5 times if the antechamber is adopted, by about 6 time if the TiN is coated only, by about 3 times if the photon absorber is made in the wall of the chamber only, by about 5 times if the electrode is installed in the beam chamber. In BEPCII, the antechamber, the photon absorber, and the TiN coating have been decided to adopt, so the electron density will be decreased about 90 times, i.e., from 1.1×10^{13} m^{-3} in the case without any restraining method to 1.3×10^{11}m^{-3}, which is lower than the threshold causing the strong head-tail instability as described in later sections.

Single bunch instability

The electron cloud can act as a short range wake field, and drive single bunch instability. Based on the head tail model [11], the code also simulates bunch blow up. In the model, transverse distributions of the electron cloud and the bunch are represented by macro particles. The bunch is longitudinally divided into slices, which interact with the EC one another and cause the distortion of the EC distribution. The macro particles in different slices can change their positions due to the synchrotron oscillation. The short range wake field and the bunch size blow-up can then be issued from the simulation. Simulation shows that the wake strength is proportional to the EC density as shown in Fig 15.

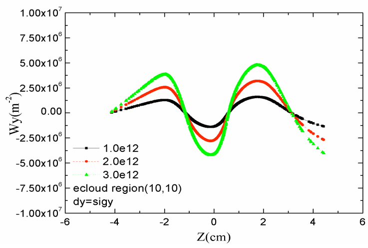

Figure 15: Short range wake due to EC.

For strong head tail instability theory, there is a criterion to calculate the threshold. It is expressed as [12],

$$\Gamma = \frac{N_b r_e \,|W_y(0)|\, \overline{\beta}_y}{16\gamma\nu_s} \le 1 \qquad (1)$$

This gives the wake field threshold of 1.47x10^{6} m^{-2} corresponding to the EC density about 9.2x10^{11} m^{-3}. Tracking the bunch for 4096 turns with different EC density, we found that the vertical bunch size increases sharply when the EC density is higher than 9.2x10^{11} m^{-3}, as shown in Fig. 16. This can be thought as the threshold of instability and is comparable with the formula.

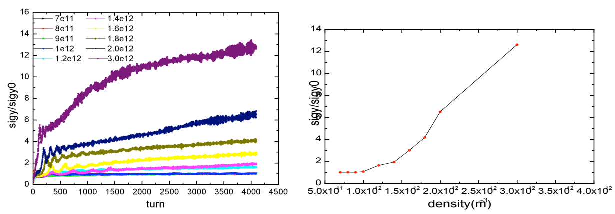

Figure. 16: Bunch size vs different EC density.

If the chromaticity is introduced in the simulation, the growth of bunch size becomes saturated and the higher the chromaticity, the stronger the damping effect, as shown in Fig. 17. This result can be compared with the experimental observation on BEPC.

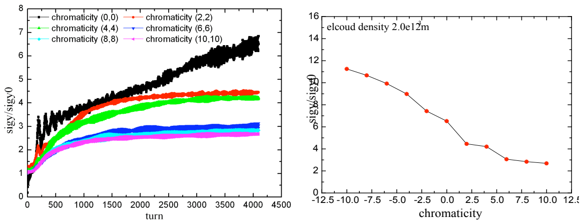

Figure 17: The bunch size versus chromaticity.

Coupled bunch instability

The couple bunch instability may occur in BEPCII as the electron density accumulated along the bunch train. In the addition to the simulation of the build up process of EC density, meantime we track the motion of 93 bunches in a train and record their positions in each turn. The growth time is obtained by fitting the amplitude of the oscillation and the coupled bunch mode can be got by FFT of the data, as shown in Fig. 18. For BEPCII with antechamber and TiN coating adopted, the EC density will decrease to 1.35x10^{11} m^{-3}. The growth time is about 4.3 ms which can be damped with feedback system.

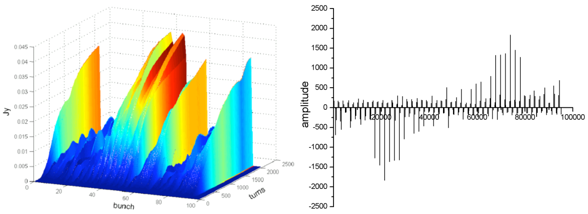

Figure 18: Growth behavior of coupled-bunch oscillation and the sidebands.

SUMMARY

A long term study on the beam electron cloud instability has been progressing in BEPC for years, and quite rich study results have been obtained from the experiments and the simulations. We have investigated experimentally the effective ways to suppress ECI, such as solenoid winding, clearing electrode, large chromaticity, octupoles etc. And with simulation, the efficiency for antechamber with photon absorber, TiN coating and clearing electrode to reduce the EC density is explored. All of these results are very meaningful for understanding the mechanism, for the design and operation of storage ring for factory like colliders. Particularly we have decided to adopt antechamber with photon absorber and TiN coating in the BEPCII to cure the ECI. The EC density can be suppressed to below the threshold of strong head-tail like instability, while the coupled bunch instability can be damped with feedback system. However some of the effects related to ECI still need further study.

ACKNOWLEDGMENTS

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